Gravitation] Coefficients and Internal Structures of the Icy Galilean Satellites: An Assessment of the Galileo Orbiter Mission

G. Schubert and D. Limonadi

1)epartment of Earth and Space Sciences

Institute of Geophysics ant] 1 'lanetary Physics

University of California

Los Angeles, California 900'24"-1567

J. D. Anderson, J. K. Campbell and G. Giampieri

J et] 'ropulsion Laboratory California Institute of Technology

Pasadena, California 91109

Submitted to *Icarus*

131 'ages

2 Figures

3 '1'able.s

Key Words: Europa, Ganymede, Callisto, Galilean satellites, gravitational field, icy satellites, satellite interiors

April 13, 1994

Running Head: **Gravitational** Coefficients of Icy Galilean Satellites

Editorial Correspondence and Proofs to:

Gerald Schubert

Department of Earth and Space Sciences

Institute of Geophysics and Planetary Physics

2810 Geology Building

University of California

Los Angeles, California 90024- 1567

(31 O) 825- 4577; gschubert@geovax.ess.ucla.edu; fax (31 O) 825- '2779

ABSTRACT

Simulated radio tracking data from one flyby of Europa, two flybys Of Ganymede, and two flybys of Callisto by the Galileo Orbiter yield estimates of the standard errors in the gravitational coefficient J_2 of 44, 8.5, and 12 (in units of 10- ') for Europa, Ganymede, and Callisto, respectively; errors in C_{22} (in units of 10-') are 12, 1.7 and 2.1. These errors are sufficiently small that the values of J_2 and C_{22} to be measured by Galileo should suffice to determine if the ice and rock in the satellite interiors are uniformly mixed or separated, so long as the bodies are in hydrostatic equilibrium.

1. INTRODUCTION

In December of 1995 the Galileo spacecraft will enter orbit around Jupiter and embark on a tour of the Jovian system that will take. it sufficiently close to the icy Galilean satellites to measure their gravitational coefficients J_2 and C_{22}. Knowledge of these coefficients will constrain models of the satellites' interiors (Hubbard and Anderson 1978; Dermott 1979; Zharkov *et al.* 1984; Mueller and McKinnon 1988) which at present run the gamut from uniform ice rock mixtures (undifferentiated objects) to rock cores surrounded by icy (water) mantles (fully differentiated bodies) to structures in between the end member undifferentiated and fully differentiated states wherein the ice and rock are partially separated (Schubert *et al.* 1986). Though it is presently widely held that all the icy Galilean satellites are differentiated and that the contrast between the endogenically modified surface of Ganymede and the old, highly cratered surface of Callisto results from a post-accretional spurt in the internal activity of Ganymede due perhaps to tidal heating early in its orbital evolution

(Malhotra 1991), there are as yet no data that conclusively establish the extent of ice-rock differentiation in the icy satellites. Therefore, the purpose of this paper is to assess whether the Galileo mission will provide the data necessary to rigorously establish the degree of ice-rock differentiation in the icy Galilean satellites. We accomplish this by estimating the accuracy with which the gravitational coefficients J_2 and C_{22} will be determined for each of the icy satellites from radio tracking data that will be received during the planned tour of the satellites by the Galileo orbiter. We then explore whether the estimated errors are small enough to discriminate with certainty between undifferentiated and differentiated models of the satellites.

II. GRAVITATIONAL COEFFICIENTS

The lowest degree and order terms in the spherical harmonic expansion of the gravitational potential U of a rotationally and tidally distorted synchronously rotating ellipsoidal satellite are

$$U = \frac{GM}{r}\left[1 - \left(\frac{\bar{a}}{r}\right)^2 J_2 \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + 3\left(\frac{\bar{a}}{r}\right)^2 C_{22} \sin^2\theta \cos 2\lambda\right] \tag{1}$$

where G is the gravitational constant, M is the mass of the satellite, r, θ, λ are spherical coordinates, $\bar{a}$ is the mean radius, the coordinate system origin is at the center of mass, zero degrees longitude ($\lambda = 0$) is along the line from the center of the planet to the center of the satellite, and J_2 and C_{22} are gravitational coefficients related to the moments of inertia A, B, C ($C > B > A$) of the satellite by

$$J_2 = \frac{C - \frac{A+B}{2}}{M\bar{a}^2} \tag{2}$$

$$C_{22} = \frac{B - A}{4 M \bar{a}^2} \tag{3}$$

The gravitational coefficients due to tidal and rotational distortion of the synchronously rotating satellite depend on the internal density structure and rheology of the satellite and can be expressed as

$$J_2 = \frac{5}{6} k_2 \left(\frac{\omega^2 \bar{a}^3}{GM} \right) \tag{4}$$

$$C_{22} = \frac{1}{4} k_2 \left(\frac{\omega^2 \bar{a}^3}{GM} \right) \tag{5}$$

where k_2 is the Love number and ω is the angular rotation rate of the satellite. The shape of the deformed satellite can be expressed as

$$\frac{a - c}{\bar{a}} = 2 h_2 \left(\frac{\omega^2 \bar{a}^3}{GM} \right) \tag{6}$$

$$b - c = \frac{1}{4} (a - c) \tag{7}$$

where a, b, c are the radii of the ellipsoid $(a > b > c)$ and $h_2 = 1 + k_2$ is another Love number. Values of k_2 are readily calculable given the radial density profile and rheological behavior of a satellite.

It is reasonable that bodies as large as the icy Galilean satellites are in hydrostatic equilibrium under the long term influence of rotational and tidal forcing. However, it is also possible that one or more of the satellites deforms nonhydrostatically to tidal and rotational forcing or has sufficient mechanical strength to either preserve a fossil bulge from an earlier time in its evolution or support internal mass anomalies unrelated to spin and tides. For the purposes of this paper we assume hydrostatic equilibrium, obtain k_2 for differentiated and undifferentiated satellite models, determine corresponding J_2 and C_{22} values from (4) and (5), assess the errors in the Galileo Orbiter's measurements of these gravitational coefficients, and ascertain if the measurements can discriminate among satellite models. The ultimate validity of the hydrostatic assumption must await the actual measurements of J_2 and C_{22} and the figures of the satellites to test the consistency of the observations with (4)- (7) and value.s of k_2 inferred from hydrostatic models.

Table 1 summarizes values of J_2 and C_{22} for a suite of differentiated and undifferentiated Table I
models of the icy satellites. Most of the models assume tidal and rotational forcing corresponding to the present orbits of the satellites. A few of the Europa and Ganymede models assume that the satellites preserve fossil tidal and rotational bulges corresponding to earlier orbital locations four percent closer to Jupiter (Malhotra 1991). Lack of differentiation does not imply absence of radial density variations since ice is somewhat compressible and also undergoes phase changes at pressures encountered in the interiors of Ganymede and Callisto. In general, values of the gravitational coefficients are larger for the undifferentiated models of the satellites than they are for the differentiated models. The densification of ice with depth results in smaller gravitational coefficients compared with similar uniform density models (Lupo 1 982). For a given interior density model, preservation of a fossil tidal bulge yields larger gravitational coefficients The major question is whether the values of J_2 and C_{22} are different enough that the Galileo measurements of these coefficients will be able to discriminate among the models? The answer depends on the size of the error or uncertainty in the Galileo measurements of J_2 and C_{22} compared with the separations in the model values of these coefficients given in Table I. In the next section we assess the errors that can be

anticipated in the Galileo measurements of J_2 and C_{22}.

III. FLYBY SIMULATIONS

The Galileo Orbiter and Atmospheric Probe were launched from the Space Shuttle Atlantis in October 1989. Following an August 1995 separation of the Probe from the Orbiter, the Orbiter is scheduled to enter Jupiter orbit on 7 December 1995. About four hours before closest approach to Jupiter, the Orbiter will encounter Io at an altitude of one thousand kilometers. This close flyby not only will provide opportunities for new Io observations, it will also reduce the required orbital insertion maneuver by an amount $\delta V = 175$ m s^{-1}. The subsequent orbiter mission will consist of eleven orbital revolutions, each orbit designed for a close flyby of either Europa, Ganymede, or Callisto. Of these eleven orbits, five will yield satellite gravity fields to the second degree and order in spherical harmonics.

Previously, we performed simulations of satellite flybys using JPL's Orbit Determination Program (ODP), the software we will use for the actual data analysis (Campbell 1984). We simulated as closely as possible the analysis of anticipated coherent Doppler data requested of the Deep Space Network (DSN) in support of our investigation. We have described elsewhere the Galileo radio science system and the full range of radio science investigations selected for the Galileo Mission (Anderson *et al.* 1992, Howard *et al.* 1992). When previously predicting results from the satellite gravity investigation, we assumed the then current mission profile of two Europa flybys during orbital revolutions 4 and 5, three Ganymede flybys on revolutions 1, 2, and 10, and three Callisto flybys on revolutions 3, 6, and 11. We predicted accuracies in the two gravity coefficients J_2 and C_{22} of 68 and 14 respectively for 10, 40 and 10 for

Europa, 15 and 2 for Ganymede, and 96 and 2 for Callisto, all in units of 10^{-6}.

More recently, we have developed software for general flyby gravity analyses based on a variation of parameters method (Anderson and Giampieri 1994). When applied to the Galileo satellite flybys, we find that this software predicts the same accuracies for J_2 and C_{22} as our earlier ODP analysis. Here we report on the application of the new software to an evaluation of a recently redesigned satellite tour.

Because of a failure in the scheduled May 1991 unfurling of the Orbiter's high-gain antenna, the Galileo Project in 1993, working in close collaboration with its Project Science Group, completely redesigned the previously selected tour. A redesign was necessitated by a significant reduction in telecommunication bit rate using the Orbiter's low-gain antenna. However, the impact of a low-gain antenna mission on the generation of coherent Doppler data was of small concern. We lost the capability to generate coherent data at X band (3.6 cm wavelength), but retained the capability at S band (13 cm wavelength). Although there is an advantage at X-band in that noise introduced by propagation of the radio signal through solar plasma is reduced at the shorter wavelength, roughly by a factor of the wavelength ratio squared (factor of 13 noise reduction over S band), we always viewed the generation of X-band data for the satellite flybys as problematical. Unlike more recent spacecraft that use the NASA standard transponder operating at X band, the Galileo orbiter's telecommunication system closely resembles the earlier Voyager S-band system. The basic Galileo system was upgraded by adding X-band hardware specifically for Radio Science investigations (Anderson *et al.* 1992, Howard *et al.* 1992). In all our earlier error studies, we assumed S-band capability for the satellite flybys, the standard operating mode. In effect we have been assuming a low-gain antenna capability all along.

We make one exception to the minimal impact of the low-gain antenna mission. Because of the determinism of orbital mechanics, the 10 flyby and the orbital insertion will occur when Jupiter is only 8.8° from solar conjunction. In our previous error studies we assumed au S-band capability appropriate for solar elongation angles greater than 80°, but we recognized that coherent X-band data would be required for the 10 flyby near solar conjunction. Without X baud, we now downgrade our earlier accuracy predictions 011 J_2 and C_{22} for 10 from 68 and 14, respectively, to 610 and 68 (in units of 10^{-}‘). Note that the errors arc not linear in the expected solar plasma. noise because wc have accounted for other systematic errors, most notably small non-gravitational accelerations from spacecraft systems and from solar radiation.

The orbital characteristics of the five flybys useful for gravity fields arc given in Table 11. Table 2
For completeness wc include Io on Orbit O. The parameters of direct concern are the flyby closest approach distance r_{CA}, the flyby velocity V, Jupiter's solar elongation angle SEP at the time of the flyby, the latitude ϕ of closest approach, and the orbital inclination I, where the last two angles are referenced to the satellite's equator. The geometry of the six flybys is shown in Figures 1 and 2, including the directions of Earth and Jupiter. The Figs 1,2
Earth occultation zones arc shown simply to indicate that continuous Doppler data can be generated during the flyby. Most of the flybys unsuitable for gravity fields were designed for Earth occultation] in support of the Radio Science atmospheric investigation. From the viewpoint of Radio Science, about half of the flybys will return atmospheric data ant] about half will return gravity data. For any given flyby, the two investigations arc mutually

exclusive.

The results of our covariance analysis are given in the last two rows of Table 11. In computing expected errors in J_2 and C_{22}, we assumed the errors in all other gravity harmonics are zero. We included the monopole term (GM) in the error analysis however, along with the orbital parameters r_{CA} and V, a total of five parameters. We assumed continuous Doppler data over a time interval of about $20 r_{CA}/V$ centered on closest approach. We accounted for systematic error by limiting the root N error improvement to a factor of two, thereby restricting the data to only four independent measurements of the Doppler curve. We sampled the Doppler curve at 60 s intervals and assumed a 1.0 mm s^{-1} standard error in each measurement of range rate. By comparing results from the new software with our previous full simulations using data analysis software (ODP), we concluded that this simplified approach to the covariance analysis is realistic.

We made one more computation of error. By combining the simulated data from the two Ganymede flybys and the two Callisto flybys, we predicted a significant improvement in J_2 and C_{22} for those two satellites. Physically, a far better determination of the global gravity field can be achieved by overflying two regions of the satellite rather than just one. For Ganymede, the combination of a near polar flyby with a flyby at moderate inclination is particularly impressive. We summarize in Table III our final error predictions, including results from combining data for Ganymede and Callisto. Table 3

IV. DISCUSSION AND CONCLUSIONS

Figure 3 summarizes the values of the gravitational coefficients for the models of Europa, Fig. 3

Ganymede and Callisto given in Table 1 and compares these values with the error estimates for J_2 and C_{22} given in Table 111. The anticipated errors in both J_2 and C_{22} for Ganymede are so small that discrimination between differentiated and undifferentiated states of the satellite should be readily achievable. It may even be possible to distinguish among models of the interior of Ganymede with different degrees of differentiation. The error bars on the gravitational coefficients of Europa are larger than they are for Ganymede, but Figure 3 shows that it may still be possible to distinguish differentiated from undifferentiated interior states unless the actual measurements of J_2 and C_{22} fall midway between the values of these coefficients for the 2-layer and undifferentiated models. The largest error bars occur for Callisto, but even in this case the error in C_{22} may permit assessment of the degree of differentiation of the satellite.

In summary, Doppler tracking of the Galileo Orbiter is expected to provide sufficently accurate determinations of the gravitational coefficients J_2 and C_{22} of the icy Galilean satellites that it should be possible to establish with high confidence whether the satellites are differentiated. Interpretation of the actual measurements could be complicated by nonhydrostatic effects (Mueller and McKinnon 1988), including the preservation of fossil tidal bulges, but such effects should be identifiable by inconsistency with hydrostatic theory, and if present will in themselves be enlightening.

Acknowledgments

This work was supported by NASA through the Planetary Geology and Geophysics Program (NAGW 2086) and through the Galileo Project (JPL 958693) and by the National

Research Council through an agreement with the Nationnal Aeronautics and Space Administration. Some sections of the paper represent one phase of research performed at the Jet Propulsion Laboratory of the California Institute of Technology, which is under contract to the National Aeronautics and Space Administration.

References

ANDERSON, J. D. AND G. GIAMPIERI 1994. Variation of parameters for flyby orbits. [*In preparation*]

ANDERSON, J. D., J. W. ARMSTRONG, J. K. CAMPBELL, F. B. ESTABROOK, T. P. KRISHER, AND E. L. LAU 1992. Gravitation and celestial mechanics investigations with Galileo. *Space Sci. Rev.* **60**, 591-610.

CAMPBELL, J. K. 1984. Determination of satellite gravity harmonics from Galileo radio tracking data. *Bull. Amer. Astron. Soc.* **16**, 705.

DERMOTT, S. F. 1979. Shapes and gravitational moments of satellites and asteroids. *Icarus* 37, 310-321.

HOWARD, H. T., V. R. ESHLEMAN, D. P. HINSON, A. J. KLIORE, G. F. LINDAL, R. WOO, M. K. BIRD, H. VOLLAND, P. EDENHOFER, M. PÄTZOLD, AND H. PORSCHE 1992. Galileo radio science investigations. *Space Sci. Rev.* **60**, 565-590.

HUBBARD, W. B. AND J. D. ANDERSON 1978. Possible flyby measurements of Galilean satellite interior structure. *Icarus* **33**, 336-341.

LUPO, M. J. 1982. Mass-radius relationships in icy satellites after Voyager. *Icarus* **52**, 40-53.

MALHOTRA, R. 1991. Tidal origin of the Laplace resonance and the resurfacing of Ganymede. *Icarus* 94, 399-412.

MUELLER, S. AND W. B. MCKINNON 1988. Three-layered models of Ganymede and Callisto: Composition, structures, and aspects of evolution. *Icarus* **76**, 437-464.

SCHUBERT, G., T. SPOHN, AND R. T. REYNOLDS 1986. Thermal histories, compositions

SCHUBERT, G., T. SPOHN, AND R. T. REYNOLDS 1986. Thermal histories, compositions and internal structures of the moons of the solar system. In *Satellites* (J. Burns and M. S. Matthews, Eds.), pp. 224-292. Univ. of Arizona Press, Tucson.

ZHARKOV, V. N., V. V. LEONTJEV, AND A. V. KOZENKO 1985. Models, figures, and gravitational moments of the Galilean satellites of Jupiter and icy satellites of Saturn. *Icarus* 61, 92-100.

TABLE I. Gravitational coefficients of icy satellite models.

Model	Density Core/Mantle/Surface (10^3 kg m^{-3})	$R/R_{Satellite}$ Core/Mantle	J_2 (10^{-6})	C_{22} (10^{-6})	Notes, References Z- Zharkov *et al.* (1985) L- Lupo (1982)
		Europa			
Undifferentiated					
a	3.01	1	629	189	Uniform Density, Z
b	3.01	1	705	211	Unform Density, Fossil Bulge
2-Layer					
c	3.52/1.00	0.923	485	146	Z
d	3.52/1.00	0.923	521	164	Fossil Bulge
3-layer					
e	5.00/3.28/1.00	0.480/0.923	434	130	Z
		Ganymede			
Undifferentiated					
a	1.93	1	240	72	Uniform Density, Z
b	1.93 (mean)	1	212	64	Depth Dependent Density, Z
c	1.93	1	268	80	Uniform Density, Fossil Bulge
2-Layer					
d	1.00/3.00	0.774	141	12	Z
e	0.90/3.52	0.732	118	35	Z
f	1.93 (mean)	1	128	39	Depth Dependent Density, L
g	1.00/3.00	0.774	162	51	Fossil Bulge
3-Layer					
j	5.0/3.28/0.90	0.379/0.732	111	33	Z

Callisto

Undifferentiated					
a	1.83		**45**	14	Uniform Density, Z
b	1.83		40	12	Depth Dependent Density, L
c	1.83		52	**16**	Uniform Density, Fossil bulge
2-Layer					
d	3.00/1 .00	0.746	**27**	8	Z
c	3.52/0.90	0.708	**23**	7	Z
f	1.83 (mean)	1	**25**	7	Depth Dependent Density, 1,
g	3.00/1 .00	0.746	**29**	9	Fossil bulge
3-Layer					
h	5.00/3.28/0.90	0.368/0.708	21	6	Z

TABLE II. Orbital parameters for six satellite flybys.

	Orbit 0	Orbit 1	Orbit 2	Orbit 3	Orbit 10	Orbit 11
	Io	Ganymede	Ganymede	Callisto	Callisto	Europa
r_{CA} (km)	2815	3131	2831	3496	2928	2696
V (km s^{-1})	15.0	7.9	8.0	8.0	8.2	5.5
ϕ	-1.6°	24.7°	84.6°	13.7°	4.8°	65.5°
i	7.7°	26.5°	86.2°	13.7°	4.8°	65.5°
SEP	8.8°	179.9°	113.4°	61.1°	138.8°	89.0°
σ_{J_2} (10^{-6})	610	60	31	168	300	44
$\sigma_{C_{22}}$ (10^{-6})	68	9.3	6.8	28	6.9	12

Orbital data for the current satellite tour are from the Galileo Navigation Team (J. R. Johannesen, private communication). Orbital parameters are defined in the text. For each flyby the expected standard errors for the gravity harmonics are listed in the last two rows.

TABLE III. Predicted standard errors for gravity harmonics.

	J_2 (10^{-6})	C_{22} (10^{-6})
Io	610	68
Europa	44	12
Ganymede	8.5	1.7
Callisto	12	2.1

Figure Captions

Fig. 1. Geometry of three satellite flybys suitable for gravity field determinations. The plane of the flyby trajectory is in the page, with the direction of the orbital angular momentum out of the page. Directions to the Earth and Jupiter projected on the orbital plane are indicated. The zone of' Earth occultation is shown. The tick marks are at two-minute intervals. The altitude h, latitude (lat) with respect to the satellite equator, and flyby velocity V are indicated. (a) Io flyby, Orbit O, 1995 December 'i', 17:46:51 ET. (b) Ganymede flyby, Orbit 1, 1996 July 4, 10:02:03 ET. (c) Ganymede flyby, Orbit 2, 1996 September 6, 19:00:28 ET.

Fig. 2. Same as Fig. 1. (d) Callisto flyby, Orbit 3, 1996 November 4, 13:31:46 ET. (c) Callisto flyby, Orbit 10, 1997 September 17, 00:21:57 ET. (F) Europa flyby, Orbit 11, 1997 November 6, 21:49:38 ET.

Fig. 3. Comparison of values of J_2 and C_{22} for models of Europa, Ganymede, and Callisto with error estimates of these gravitational coefficients from simulated Galileo Orbiter radio tracking.

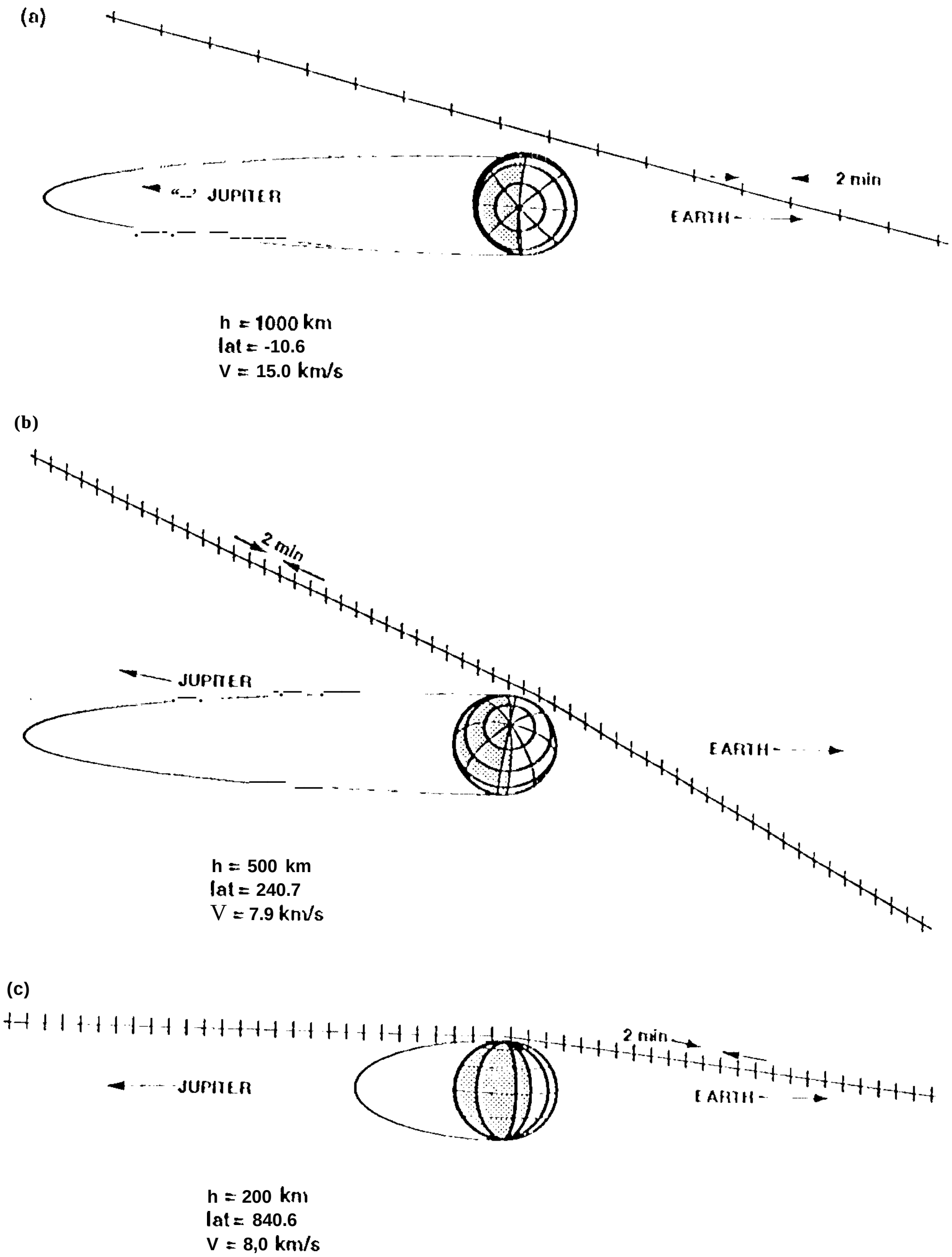

(a)
2 min
JUPITER
EARTH
h = 1000 km
lat = -10.6
V = 15.0 km/s
(b)
2 min
JUPITER
EARTH
h = 500 km
lat = 240.7
V = 7.9 km/s
(c)
2 min
JUPITER
EARTH
h = 200 km
lat = 840.6
V = 8,0 km/s

Fig. 1

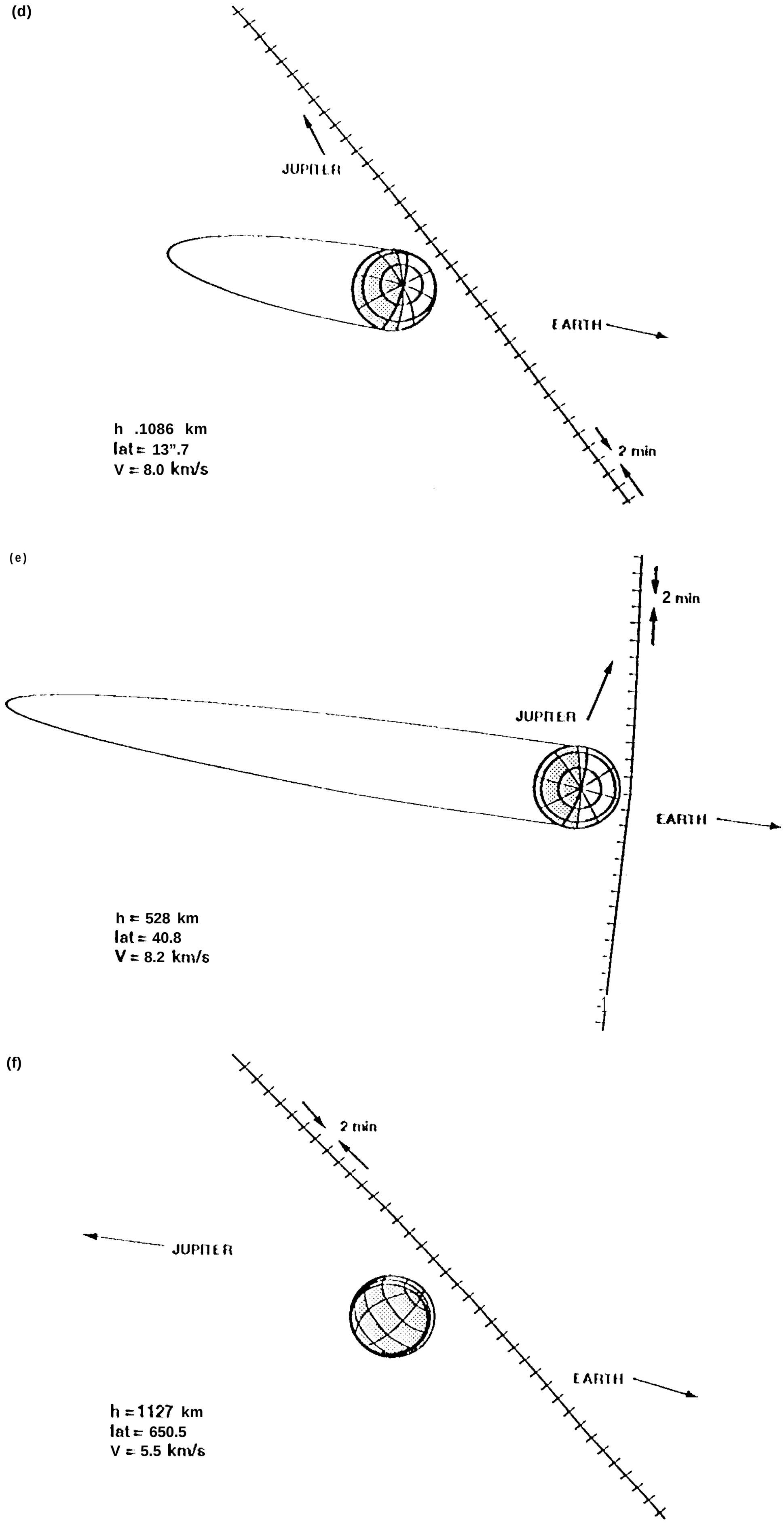
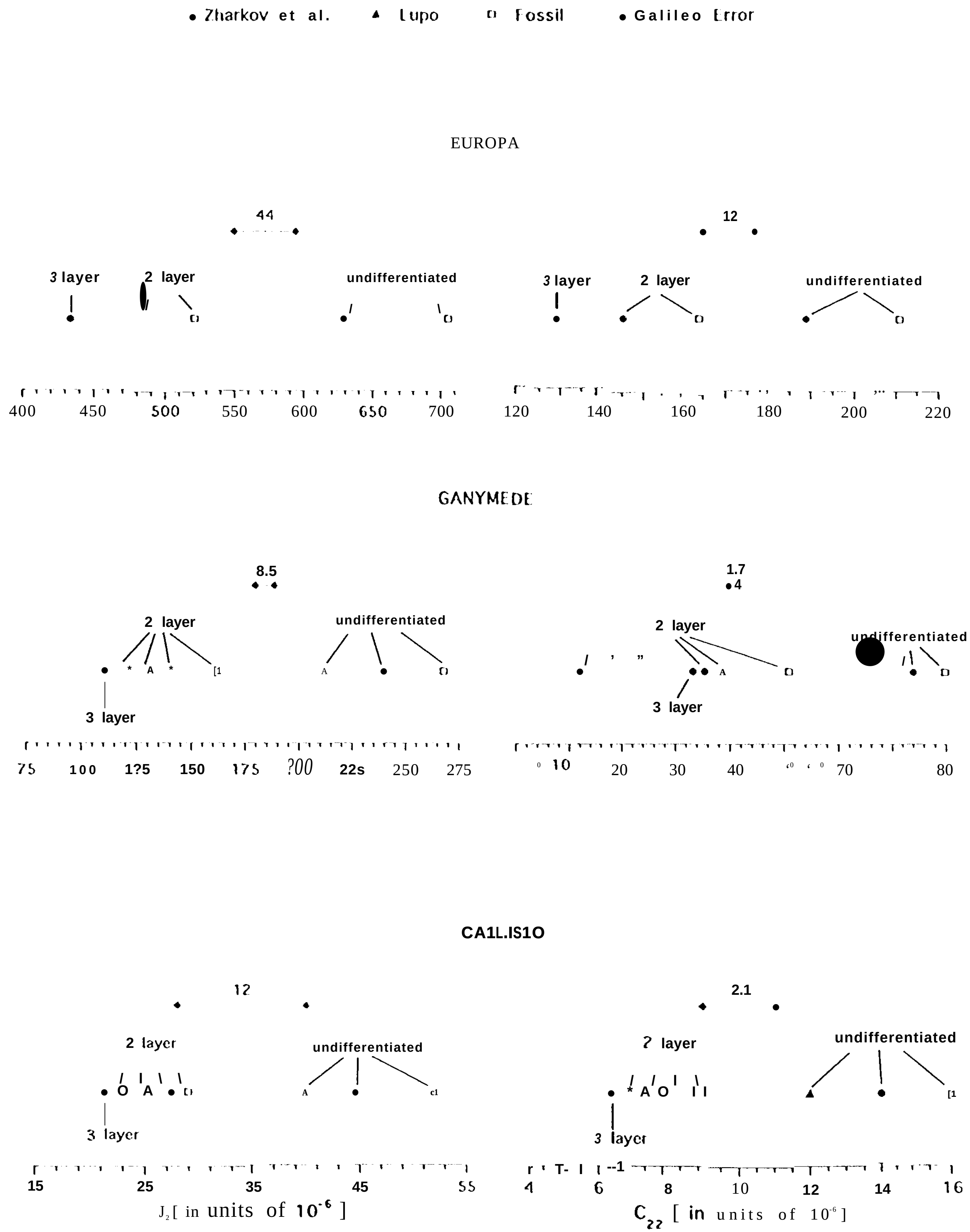

(d)
JUPITER
EARTH
2 min
h .1086 km
lat= 13".7
V = 8.0 km/s
(e)
2 min
JUPITER
EARTH
h = 528 km
lat = 40.8
V = 8.2 km/s
(f)
2 min
JUPITER
EARTH
h = 1127 km
lat = 650.5
V = 5.5 km/s

Fig. 2


Zharkov et al.
Lupo
Fossil
Galileo Error
EUROPA
44
12
3 layer
2 layer
undifferentiated
400 450 500 550 600 650 700
120 140 160 180 200 220
GANYMEDE
8.5
1.7
2 layer
3 layer
undifferentiated
10 20 30 40 70 80
12
2.1
2 layer
3 layer
undifferentiated
15 25 35 45
4 6 8 10 12 14 16
J_2 [in units of 10^{-6}]
C_{22} [in units of 10^{-6}]